where $\rho_b(t)$ and $\rho_{b'}(t)$ are to be determined from the following set of equations corresponding to (10):

$$\partial\rho_{a'}{}^{\alpha}/\partial t = -i[H_e{}^{\alpha},\rho_{a'}{}^{\alpha}] - (\gamma_a+\gamma)\rho_{a'}{}^{\alpha} + 2\pi\mathbf{H}_{a0}\rho_0{}^{\alpha}\mathbf{H}_{0a}, \quad (36a')$$

$$\partial\rho_{a}{}^{\alpha}/\partial t = -i[H_e{}^{\alpha},\rho_{a}{}^{\alpha}] - \gamma_a\rho_a{}^{\alpha} + 2\pi\mathbf{H}'\rho_{a'}{}^{\alpha}\mathbf{H}', \quad (36a)$$

$$\partial\rho_{b'}{}^{\alpha}/\partial b = -i[H_e{}^{\alpha},\rho_{b'}{}^{\alpha}] - (\gamma_b+\gamma)\rho_{b'}{}^{\alpha} + 2\pi\mathbf{H}_{ba}\rho_{a'}{}^{\alpha}\mathbf{H}_{ab}, \quad (36b')$$

$$\partial\rho_{b}{}^{\alpha}/\partial t = -i[H_e{}^{\alpha},\rho_{b}{}^{\alpha}] - \gamma_b\rho_b{}^{\alpha} + 2\pi\mathbf{H}'\rho_{b'}{}^{\alpha}\mathbf{H}' + 2\pi\mathbf{H}_{ba}\rho_a{}^{\alpha}\mathbf{H}_{ab}. \quad (36b)$$

In the average over α, $\rho_0(t)$ is proportional to the unit matrix and its time dependence is given by the factor $e^{-\gamma_0 t}$. Since the decay $0\rightarrow a$ is not observed and $\gamma_0 \ll \gamma_a$, this is still true for $\rho_{a'}(t)$. The desired solutions of the Eqs. (36b′) and (36b) are then

$$\rho_{b'}(t) = \text{const}\frac{1}{N}\sum_{\alpha}\int_0^t dt' e^{-(\gamma_a+\gamma)(t-t')}e^{-\gamma_0 t'} \times U^{\alpha}(t,t')\mathbf{H}_{ba}\mathbf{H}_{ab}U^{\alpha}(t,t')^{+} \quad (37)$$

and

$$\rho_b(t) = \text{const}\left\{\frac{1}{N}\sum_{\alpha}\int_0^t dt'\frac{\gamma}{\gamma_a}e^{-\gamma_b(t-t')}e^{-\gamma_0 t'}U^{\alpha}(t,t') \times \mathbf{H}_{ba}\mathbf{H}_{ab}U^{\alpha}(t,t')^{+} + \frac{1}{N}\sum_{\alpha}\int_0^t dt'\int_0^{t'} dt'' \times 2\pi e^{-\gamma_b(t-t')}e^{-(\gamma_a+\gamma)t'-t''}e^{-\gamma_0 t''}U^{\alpha}(t,t') \times \mathbf{H}'U^{\alpha}(t',t'')\mathbf{H}_{ba}\mathbf{H}_{ab}U^{\alpha}(t',t'')^{+}\mathbf{H}'U^{\alpha}(t,t')^{+}\right\}. \quad (38)$$

Inserting (37) and (38) in (35), we have clearly three terms in the correlation function. The first term in (38) describes those cases where the electron shell decays while the nucleus is still in the level a; the second term describes decays of the electrons during the life of the state b; (37) describes the nuclei whose electrons remain in the excited state during the life of the state b. For large γ, the first term in (38) is predominant; for small γ, (37) is predominant. In both cases we have the same correlation function as in Sec. III.

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Gamma Radiation from Proton Bombardment of Li^7†

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The capture γ rays from the reaction $Li^7(p,\gamma)$ have been investigated by measuring excitation functions and angular distributions. In addition to the well-known resonance at 441 kev, the excitation curve exhibits resonance at 1030 kev in proton bombarding energy corresponding to an excited state at 18.14 Mev in Be^8. Near this resonance the γ rays have a nonisotropic angular distribution with fore-and-aft asymmetry. The yield integrated over this resonance corresponds to a radiation width given by $\omega\Gamma_\gamma = 2$ ev.

IN the bombardment of Li^7 by protons, γ rays of 15- and 18-Mev energy are produced in the capture reaction, $Li^7(p,\gamma)$. In addition, the first excited state of Li^7 is produced by inelastic scattering of the protons and the decay of this state results in the emission of 478-kev γ rays, the over-all process being indicated by $Li^7(p,p'\gamma)$. The excitation curve for the 478-kev γ rays exhibits resonance[1] at 1030-kev bombarding energy and the behavior of the inelastically scattered protons near this resonance has recently been studied in this laboratory.[2] In addition, the cross section for the protons elastically scattered by Li^7 shows a strong anomaly near this resonance.[3] The present investigation was conducted to determine whether or not the capture γ rays for $Li^7(p,\gamma)$ are resonant at this energy.

Evaporated lithium targets were bombarded with protons from the 2-Mev electrostatic accelerator of the Kellogg Radiation Laboratory. The γ rays were detected with a scintillation counter made of a NaI(Tl) crystal $1\frac{1}{2}$ in. in diameter and 2 in. long, cemented to a 5819 photomultiplier tube. The output was fed into a linear amplifier and to two discriminators, each having its output pulses counted on decade scalers. The system was unable to discriminate between the 15- and 18-Mev γ rays from the $Li^7(p,\gamma)$ reaction. One discriminator was set to count all events over 5 Mev, and the second was set to count the 478-kev (soft) γ rays from the

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[1] Brown, Snyder, Fowler, and Lauritsen, Phys. Rev. **82**, 159 (1951).
[2] Mozer, Fowler, and Lauritsen, Phys. Rev. **93**, 829 (1954).
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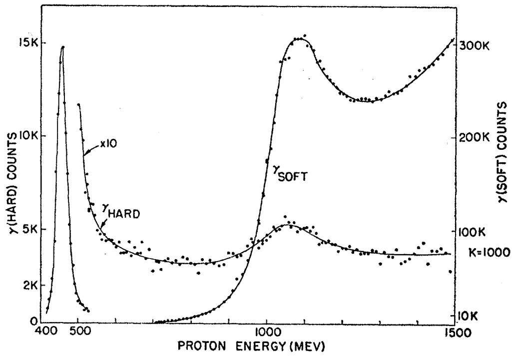

FIG. 1. The excitation function for the various γ rays from the reaction Li^7+p. The soft γ rays are from $Li^7(p,p'\gamma)Li^7$. The hard γ rays are from $Li^7(p,\gamma)$.

reaction $Li^7(p,p'\gamma)$. Typical excitation curves are shown in Fig. 1. The soft γ-ray excitation function agrees with that of Brown, Snyder, Fowler, and Lauritsen.[1] The rise in cross section beyond the resonance is mainly due to the rapid increase in penetration factor with energy of the outgoing proton. The hard γ rays from the reaction $Li(p,\gamma)$ show the well known 441-kev resonance and the 1030-kev resonance as well.

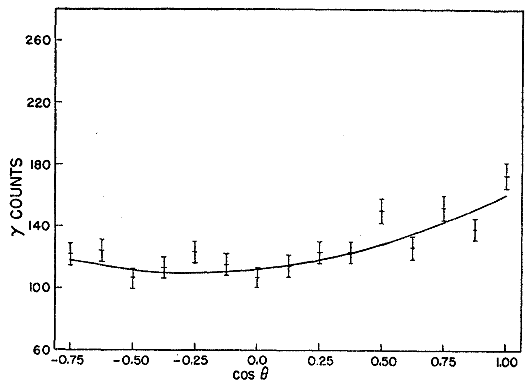

FIG. 2. The angular distribution of hard γ rays at a proton energy of 880 kev. The curve is $W(\theta)=112+16\cos\theta+32\cos^2\theta$.

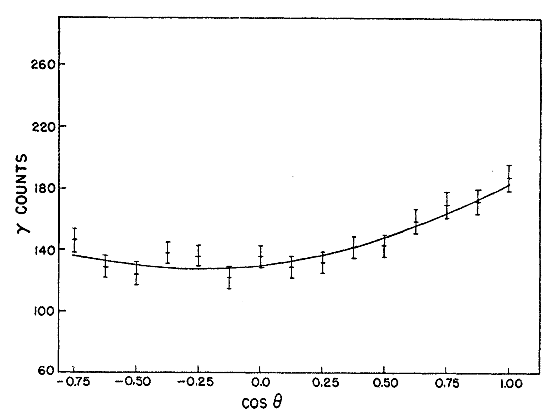

FIG. 3. The angular distribution of hard γ rays at a proton energy of 960 kev. The curve is $W(\theta)=130+18\cos\theta+36\cos^2\theta$.

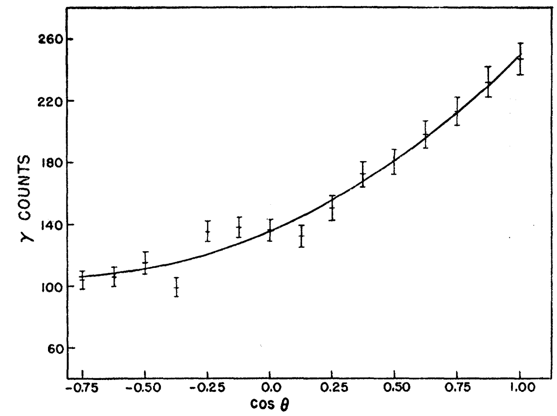

FIG. 4. The angular distribution of hard γ rays at a proton energy of 1060 kev. The curve is $W(\theta)=134+70\cos\theta+44\cos^2\theta$.

The target thickness was about 30 kev. The hard γ-ray counts are the measured number corrected for a small background and the scattering of the points is to be expected from the small number of counts. The soft γ-ray counts are the measured number corrected for background and hard γ-ray counts.

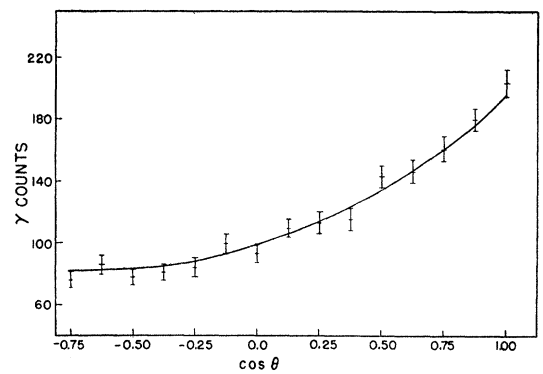

FIG. 5. The angular distribution of hard γ rays at a proton energy of 1140 kev. The curve is $W(\theta)=98+56\cos\theta+40\cos^2\theta$.

In order to show that the observed resonance of the hard γ rays was not due to pile-up of the soft γ-ray

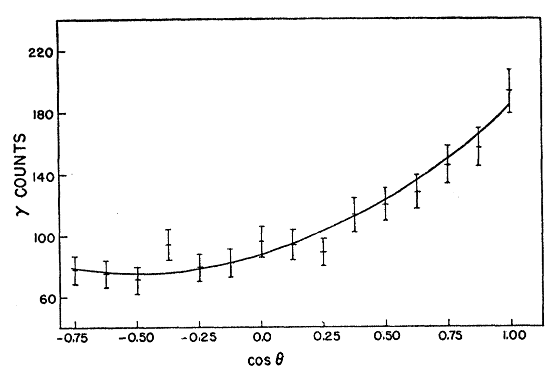

FIG. 6. The angular distribution of hard γ rays at a proton energy of 1240 kev. The curve is $W(\theta)=88+48\cos\theta+48\cos^2\theta$.

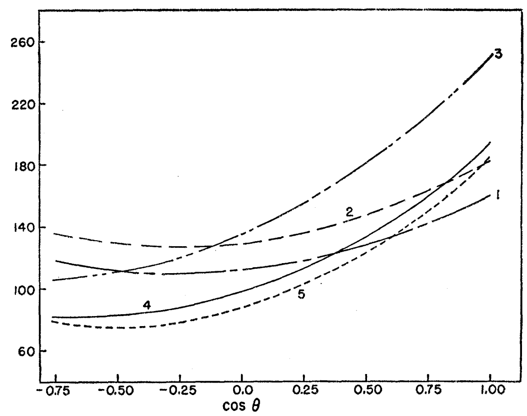

FIG. 7. The curves of Figs. 2–6. Curve 1 is for a proton energy of 880 kev; curve 2 for 960 kev; curve 3 for 1060 kev; curve 4 for 1140 kev; and curve 5 for 1240 kev.

counts, an experiment was devised to determine the importance of pile-up counts. A Cs^{137} source, which emits 661-kev γ rays, was put near the counter at a distance such that the counting rate in the soft γ-ray channel was about twice the maximum $Li^7(p,p'\gamma)$ counting rate. During a period of time that corresponded to an average run, the number of counts in the hard γ-ray channel was found to be slightly, but not significantly, above the background. Considering the higher energy and greater counting rate, it is clear that no appreciable number of soft γ rays were counted in the hard γ-ray channel.

By integrating the area under a resonance curve one obtains numbers proportional to $\omega\Gamma_\gamma/E_p$ (neglecting the change of γ-detection efficiency), where Γ_γ is the γ-ray radiation width, ω is a statistical factor, and E_p is the proton energy. The value of $\omega\Gamma_\gamma$ for the 441-kev resonance[4] is 9.4 ev. Performing the integrations over

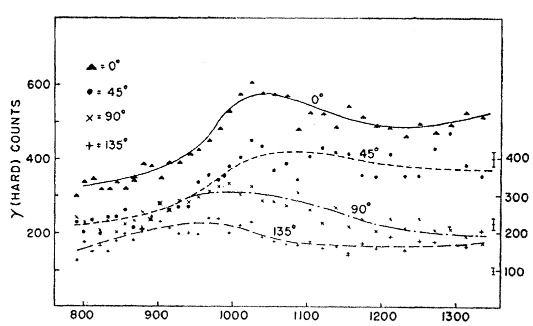

FIG. 8. Excitation functions of the hard γ rays for various angles of observation.

[4] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **76**, 314 (1949).

the two resonances one obtains a value of approximately 2 ev for $\omega\Gamma_\gamma$ at the 1030-kev resonance.

In order to obtain more information about the 1030-kev resonance, the angular distributions of the γ rays were measured at several proton energies. These distributions are shown in Figs. 2–6. The target thickness was about 60 kev. The curves through the measured points correspond to the formulas given in the captions. Figure 7 shows these curves without the measured points. Figure 8 shows the excitation functions for various angles of observation. The curves of Fig. 7 can be expressed as

$$W(\theta)=W(\pi/2)[1+a\cos\theta+b\cos^2\theta],$$

where $W(\theta)$ is the number of counts at the angle of observation θ. Figure 9 is a plot of $W(\pi/2)$, a, and b for the different energies.

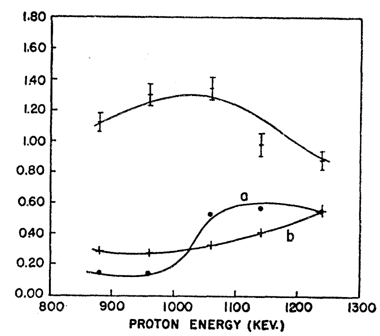

FIG. 9. Angular distribution coefficients of the hard γ rays from $Li^7(p,\gamma)$. The angular distributions are of the form $W(\theta)=W(\pi/2)[1+a\cos\theta+b\cos^2\theta]$. The coefficient $W(\pi/2)$ is divided by 100.

One important feature of Fig. 9 is the shape of the curve for a. The coefficient a is positive throughout the resonance, although the shape is approximately that to be expected from a resonance interfering with a nonresonant state of opposite parity. A simple interpretation is that the resonant part of the γ-ray cross section gives rise to a change in the coefficient a by the interference with a nonresonant part. However, the fact that a is always positive is taken to indicate that the nonresonant part itself has at least two components of opposite parity. In view of this complexity, no definite conclusions have been reached as yet about the spin and parity of the compound state at 18.14 Mev in Be^8 represented by the 1030-kev resonance.

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